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Experimental Study of the Exchange Flow Through a Horizontal Ceiling Vent in Atrium Fires

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ABSTRACTS

This study is directed at understanding an exchange flow rate through a single top vent in an atrium-type compartment with a fire experimentally and obtaining basic knowledge of physical mechanism for developing a comprehensive atrium fire model. A series of experiments was conducted with two reduced scale cubic models with propane gas burner as a heat source. Under various conditions of heat release rate and top vent area, the exchange flow rates were estimated by oxygen consumption method. The result indicates that the dimensionless exchange rate of hot/cool gas is closed to an experimental constant value obtained by salt-water experiments in the past under small vent aspect ratio condition.

1. INTRODUCTION

The object of this work is to study experimentally flow rates through a horizontal top vent in an atrium-type compartment with a fire and under relatively low cross-vent pressure differences. The results will be used to develop a comprehensive atrium fire model. From the point of designing atria for life safety (e.g., insutring safe evacuation from all threatened spaces) reliable estimates of the flow through top vents are important. For example, outward smoke movement generally leads to reduction of smoke layer temperature and thickness and inward flow of cool outside air enhances potentially hazardous mixing of the smoke through the entire atrium space. The physical phenomena have been studied by Epstein[1,2] and Jaluria[3] with salt-water experiments. Also, limited experimental work with hot/cool gas exchange was carried out by Tu[4] who used an ethyl alcohol burner heat source. Based on Epstein's experimental result, Cooper[5,6] has been developing a submodel for this kind of phenomena suitable for use in two-layer zone-type fire models. However, available data to verify and advance this kind of submodel are not adequate. The present experiments are designed to acquire required data and insights on the exchange flow process. This effort, which uses a reduced scale model with a gas burner, is similar to the liquid-fuel burner experiments of Tu [4]

2. DESCRIPTIONS OF THE EXPERIMENTS

Reduced-Scale Experiments.
Reduced scale tests were conducted to study the exchange flow rate through circular, horizontal, top-centered vents (diameter, 0.3 m, 0.2 m, and 0.1 m). A cubic test compartment (0.8 m side) was constructed of 0.05 m (0.0125 m at ceiling) thick ceramic fibre board. Fig.1 is a sketch of the test apparatus. A 0.15 m diameter natural gas (11,000 Kcal/Nm^3) burner was located flush with the floor and at the center of the enclosure. Heat release rate (0.8 - 5.6 KW) was controlled by a mass flow controller. Inside the test compartment was a thermocouple tree (type K with 0.127 mm beads) with 17 measuring points to measure gas temperature versus height. Using a vertical sliding probe, O_2 volume concentration was measured at 0.01 m, 0.40 m and 0.79 m above the floor. For future experiments, the test fixture was designed with a capability for specified uniform-flux air ventilation at the floor surface. Similar preliminary tests were carried out in a smaller test compartment (0.43 m sides, the same size as was used in [4]) and burner (0.1 m diameter), but without any ventilation capability. To allow for visual observation within the compartment, both the large and small test fixtures (refereed to below as large and small scale) were outfitted with a floor-to-ceiling glass strip in the center of

one wall. During some tests, flow visualization was carried out with the use of smoke generating pellets placed outside the compartment and near the vent opening.

Estimation of Flow Rate.

Direct measurement of the bi-direction flow through the vent is not possible. In this experiment, the exchange flow rate was estimated by using the oxygen consumption method. We suppose that heat release rate calculated from mass burning rate is nearly equal to the estimated energy release rate obtained by oxgen consumption method. Neglecting the volumetric flow rate of the fuel compared to that of the vent inlet flow, $\dot{V}_{amb}$, and for steady state this leads to

$$\dot{V}_{amb}=\frac{\dot{Q}_f}{H\mu_{amb}\rho_{amb}(1-\mu_{bot}/\mu_{amb})}\ ;\ \dot{V}_{bot}=\frac{\rho_{amb}}{\rho_{bot}}\dot{V}_{amb} \qquad (1)$$

Where μ is O_2 mass fraction, H is specific energy (13.1 MJ/kg_{O_2}), $\dot{Q}_f$ is the heat release rate of the fire, the subscripts *amb* and *bot* refer to conditions above and below the vent, respectively, or to the vent flows issuing from outside (ambient) to inside or from inside to outside the fixture, respectively.

Normalized Exchange Flow Rate and Opening Aspect Ratio.

Define the dimensionless exchange flow rate, $\dot{V}^*$,

$$\dot{V}^*=\frac{\dot{V}}{\sqrt{D^5 g\Delta\rho/\bar{\rho}}} \qquad (2)$$

where D is vent diameter, g is acceleration of gravity, ρ is density, $\bar{\rho}=(\rho_{amb}+\rho_{bot})/2$ and $\Delta\rho=(\rho_{amb}-\rho_{bot})$.
Experiments of [1] in a top-vented compartment with geometry similar to our resulted in an equation correlating $\dot{V}^*_{amb}$ vs L/D, where L is vent depth. The correlation is plotted in Fig.2. For relatively small L/D, $\dot{V}^*_{amb}$ is 0.055. For experiments with incompressible fluids (e.g., fresh-water/saltwater), $\dot{V}^*_{amb}=\dot{V}^*_{bot}$ and the crossvent pressure difference is zero. As indicated by the second of Eq.(1), this is not generally true for steady heated-air experiments. Included in Fig. 2 are data from [1],[3], and [4]. The present data are listed in Table 1. The large scale data were at steady state, at least two hours after ignition. The small scale data were at quasi-steady-state, approximately 1/2 hour after increases in fuel flow rate. The data were reduced using Eq.(1), are included in Fig.2. In the latter data reduction the μ_{bot} of Eq.(1) was estimated by the measured near-ceiling O_2 volume fraction ratio, in the case of large scale, and by the average floor-to-ceiling O_2 volume fraction ratio, in the case of the small scale. In both cases, ρ_{bot} was estimated from near-ceiling time-averaged temperature measurements. Data is included in the table only for those

Table 1. Data from the present experiments

Scale	Run No.	CONDITIONS		Temperature (deg.C)		Oxgen Concentration (Vol. %)		
		D (m)	Qf (kW)	Ambient	Ceiling	Ceiling	Center	Floor
LARGE SCALE TEST (0.80 x 0.80 x H. 0.80 m)	1	0.1	1.1	14	165	18.5	18.8	19.4
	2		1.4	15	193	17.9	18.0	18.9
	3		1.7	14	223	17.3	18.0	18.8
	4		2.0	15	245	17.1	17.4	18.2
	5		2.7	13	313	14.7	15.2	16.6
	6	0.2	2.7	9	212	18.6	18.7	19.1
	7		4.0	13	372	15.9	15.9	16.1
	8	0.3	4.0	8	243	18.8	19.2	19.3
	9		5.6	10	262	18.7	19.0	19.1
SMALL SCALE TEST (0.43 x 0.43 x H.0.43 m)		Cf. *1 Flame is unblocked. *2 Flame is blocked.				Floor - to - Ceiling Averaged		
	10	(*1) 0.1	0.66	13	215	18.5		
	11		0.88		265	17.8		
	12		1.1		292	17.6		
	13		1.3		320	17.1		
	14	(*2) 0.1	0.66	5	215	17.4		
	15		0.88		330	15.2		
	16		1.1		375	14.5		
	17	0.2	0.88	5	142	19.2		
	18		1.1		160	19.1		
	19		1.3		235	18.6		
	20		1.5		285	18.2		

Cf. D is a diameter of top vent opening. Q is a heat release Rate.
Temperature (Ceiling) is the time aberaged temperature of a few centi meter below ceiling.
Oxgen Conc.(Ceiling/Floor) is of 1 cm below/above each plane.

tests where O_2 concentrations near the ceiling were less that 0.19. This insured estimates of $(1-\mu_{bot}/\mu_{amb})$ in Eq.(1) with expected errors of less than 25 percent.

3. DISCUSSION

The small-scale data and the data of [4] compare reasonably well with the correlation of [1]. Some discrepancies with data from incompressible fluid experiments are to be expected because of the effects of large cross-vent density differences and non-zero cross-vent pressures. It is important to take these effects into account in a mathematical model of exchange flow phenomena.

The large-scale data do not correlate well with the small-scale data. One possible explanation for this, which has not yet been confirmed, is that leakage through the joints of the large fixture plays a significant role in the present, relatively-small, cross-vent pressure experiments. Leakage effects could be significant in the large scale fixtures and not in the small scale fixture because of 1) its potentially-leaky floor-ventilation design feature, 2) its large surface area, and 3) the larger cross-wall/floor pressure differences (i.e., at comparable inside temperatures). This will be investigated prior to future tests.

In the tests with the 0.1 m vent the burner flame always exhibited extended, laminar-like behavior. This was different from all other tests where the flame and its plume exhibited turbulent-like behavior. The former laminar characteristics of the flow persisted even near the elevation of the vent itself. Therefore, it is no surprise that in Fig.2 these data do not correlate well with the Epstein's data, which involved turbulent-like flows near the vent. (For practical interests, the objective of the present study is to understand the exchange flow through "real" vents under expected turbulent flow conditions). The 0.1 m "blocked" flame experiments involved tests where the axis of the laminal flame was blocked with a small metal plate, close to the burner surface, in an attempt to simulate turbulent-like behavior in the plume near the vent elevation. This was "blocked" data are definitely closer to the "turbulent-flow" correlation.

4. CONCLUDING REMARKS

1. The correlation of the dimensionless exchange flow rate ($\dot{V}^*$) vs the aspect ratio of vent (L/D), which was obtained in salt-water experiments in the past, can be applied to the compressive hot/cool gas exchange flow in a small-L/D region. However, further experiments are needed to determine an experimental constant of $\dot{V}^*$.
2. When the opening area is small enough to make flame exhibit extended laminar-like behavior, the estimated exchange flow rate becomes larger than that under fluctuating turbulent-like flame condition. It is one of tasks to find out whether this discrepancy occurrs mainly due to physical flow mechanism or only experimentation technique.

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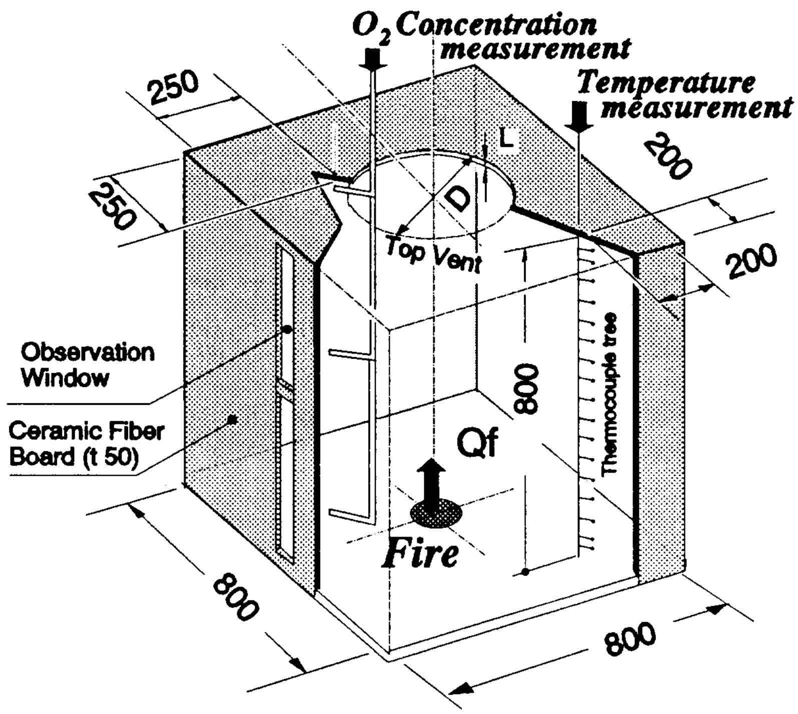

Fig.1. Sketch of experiment; dimensions in mm.

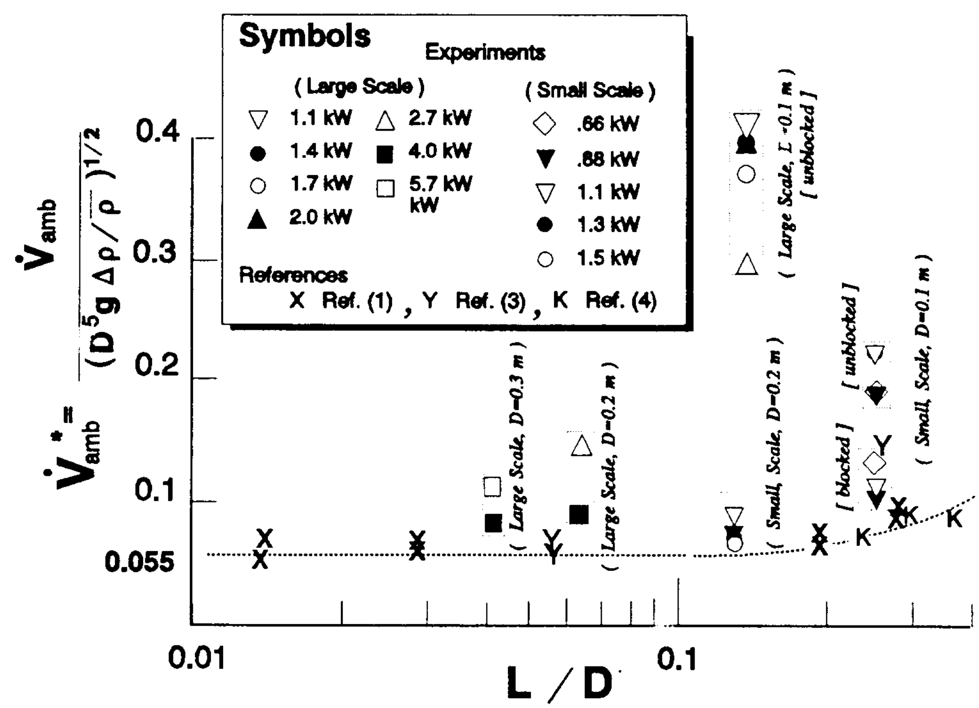

Fig.2. Plots of $\dot{V}_{*amb}$ vs L/D